Appendix N
Climate Change

Introduction

The purpose of this appendix is to provide updated analyses of potential impacts of climate change on City Light operations for the Skagit Hydroelectric Project on the Skagit River and the Boundary Project on the Pend Oreille River and lay the foundation for examining adaptation strategies. The objectives are to assess how changes in regional temperature, precipitation, and hydrology patterns affect electricity generation and demand. This appendix includes modeled hydroelectric project operations relying on a combination of published studies, generation information provided by the Northwest Power Conservation Council (NPCC), climate and hydrology modeling from the University of Washington's Climate Impact Group (CIG), CIG's Washington Climate Change Impact Assessment report (WACCIA) (CIG 2009), information in the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (FAR) (IPCC 2007), and publications from the National Academy of Science (NAS) (2008). Readers are referred to these publications for more information on the status of climate science and modeling and the regional and statewide impacts of climate change.

It is important to note that the graphs and tabular information presented in this appendix represent model output that are projections, not forecasts. Actual future conditions will likely vary from the averages presented here. Numerous sources of uncertainty are inherent in the complex modeling, so the models should not be viewed as predictive, but rather as a relative measure of deviation from past conditions. In many cases, strong annual and decadal cycles in weather patterns will continue to be a major factor driving short-term weather patterns.

Summary

The main findings of this climate change projections are:

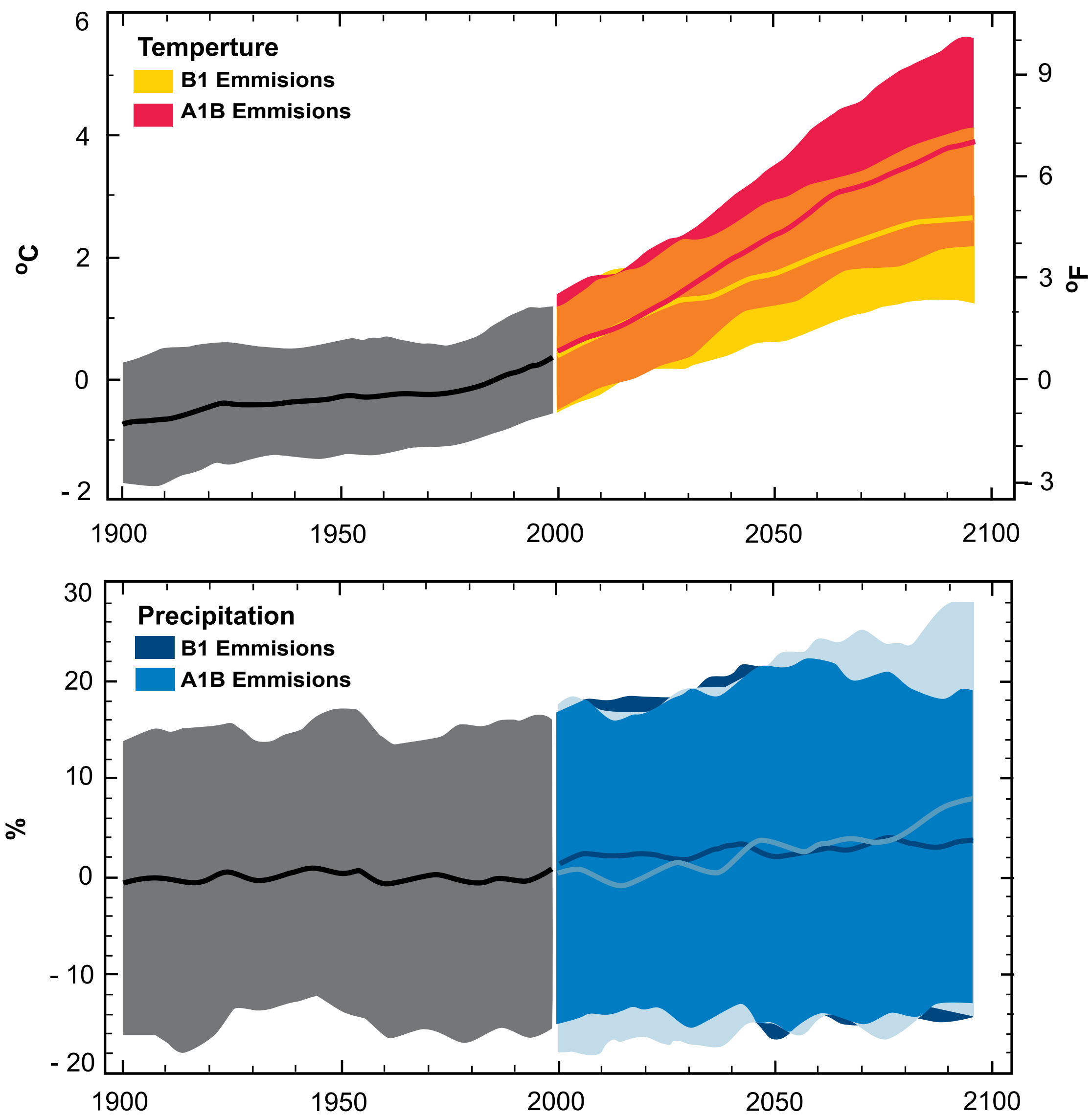
- During the 21st century, climate change is likely to result in changes to Skagit Hydroelectric Project inflows and result in operational modifications to maximize generation and meet recreation, fisheries, and flood control obligations. These changes will likely include reservoir refill timing and seasonal water release patterns.
- In general, more precipitation and runoff under the 2040s climate may make it possible to achieve approximately 20% increases in Skagit generation during the fall and winter when service area demand peaks. However, because more precipitation will fall as rain rather than snow and because of the high degree of uncertainty about intensity of storm events, it is also possible that more water will be spilled, reducing generation. Low flows are likely to reduce summer generation by an average of approximately 30%.
- Under the 2040s climate, optimized operation of the Skagit Project will require an average of 40 feet less drawdown of Ross Reservoir during the fall-spring time period to ensure refill by July.
- Generation at Boundary is dependent on upstream operations and is more difficult to project under future climate conditions. Current modeling indicates that Annual Boundary generation would decline by approximately 7% under the 2040s climate.
- In addition to the uncertainty inherent in climate model projections, there remain major issues that must be better understood for long-term operational adaptation. If the relative snowpack and glacier contribution decrease significantly, electricity generation could be further impacted. In addition, reduced glacial input in the Skagit watershed could increase water temperatures and impact our ability to protect fisheries resources downstream of the dams. There is also the possibility that in the future, the Federal Energy Regulatory Commission

(FERC) and state and federal fisheries regulatory agencies could mandate different flows for fish protection, which would affect the project operation optimization. Also, there is a possibility of the Corps of Engineers changing flood control management because peak flows in the lower Skagit valley are anticipated to dramatically increase.

Climate Change in the Pacific Northwest

The average temperature in the Pacific Northwest is expected to increase through the 21st century. The WACCIA (CIG 2009) projects that the annual temperature under scenarios A1B (medium-level greenhouse gas emissions) and B1 (low-level greenhouse gas emissions) in the Pacific Northwest will increase, on average, 1.1°C (2.0°F) by the 2020s, 1.8°C (3.2°F) by the 2040s, and 3.0°C (5.3°F) by the 2080s, compared with the 1970 - 1999 average (CIG 2009) (Figure 1). In western Washington, the frequency of hot days is projected to increase from 30 days per year currently to 50 days per year by the 2040s (CIG 2009). The future trend in precipitation is much less clear than temperature. Regional projections suggest an overall change in annual precipitation of +1% to +2% (Figure 1), with some models projecting wetter autumns and winters and drier summers. Precipitation intensity is also expected to increase. Current projections indicate that precipitation intensity in the North Cascades

Figure 1. PNW temperature and precipitation for the 20th and 21st century model simulations, relative to the 1970-1999 average (CIG 2009).

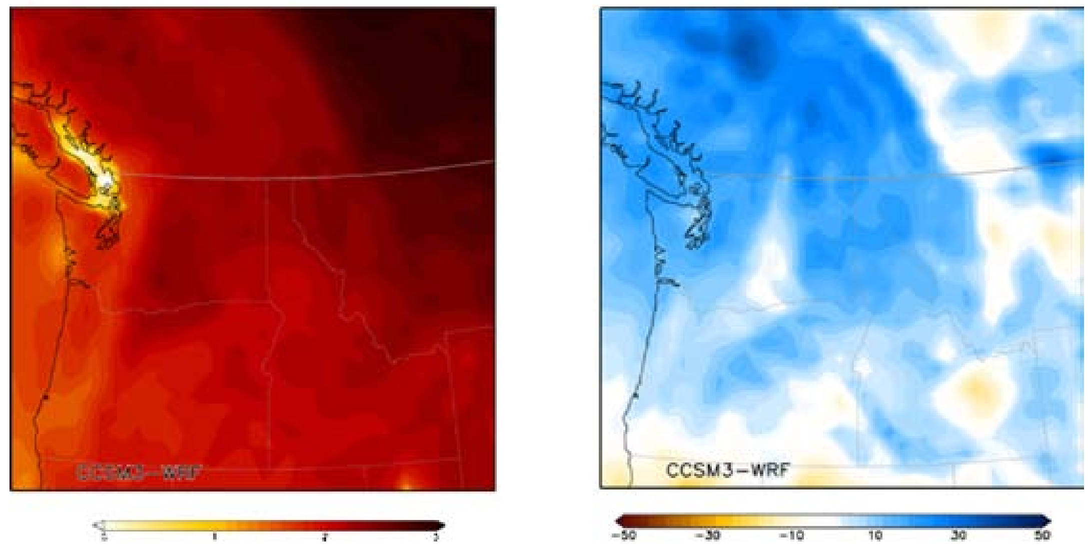


and Northeast Washington could increase 5-10%, meaning that we will have more large storms. Regional models show increasing fall temperatures from marine coastlines to inland areas and a pattern of increased fall precipitation in the northern portions of Washington (Figure 2).

An amplifying effect of climate change on hydrology of rivers and streams is expected due to the projected reduction in snowpack over the next century, continuing a trend that has been observed in recent decades (CIG 2009). Cascades spring snowpack declined 23% between 1930 and 2007, with 70% of that being from climate change (Stoelinga et al. 2009). Casola et al. (2009) reported that spring snow-water equivalent (SWE) in the Puget Sound Cascades basin declined by 8%-16% over the past 30 years from global warming and estimated a 16% decline in spring snowpack per degree Celsius temperature increase in the Cascades. This would result in an 11%-21% by the 2040s. CIG (2009) reported that April 1 SWE could decline by up to 65% by the 2080s. However, shorter-term weather patterns and decadal cycles can cause very high snowpack in any given year.

Figure 2. Fall difference between 1990s and 2040s in Pacific Northwest temperature and precipitation based on regional climate model (CIG 2009).

Temperature | **Precipitation (% change)**



Impact on City Light

City Light used analysis conducted by CIG to evaluate hydrologic impacts to its Boundary and Skagit projects. CIG analysis included simulated monthly and daily stream flows for historical climate (1970-1999) as well as climates of the 2020s (2010-2039), 2040s (2030-2059), and 2080s (2070-2099) under two Greenhouse Gas (GHG) emission scenarios-A1B and B1. Methodology used by CIG can be found in CIG (2010). For the Skagit Project, an internal Excel-based model with Frontline Solver™ add-on was used to model the CIG hydrology projections and evaluate specific impacts on project operations and generation. The Excel-based Skagit operations model was used to optimize Ross, Diablo, and Gorge outflows, using estimated monthly energy prices and FERC license constraints on reservoir levels for recreation and flood control and instream flows for fish protection downstream of Gorge Powerhouse. Fisheries requirements in the model were simplified because in practice the flows are adjusted from daily based on consultation between fisheries biologists and power managers and are difficult to anticipate and include in a model. For Boundary, the CIG analyses were used along with generation analysis completed in 2009 by the NPCC for its Columbia River system in its Sixth Power Plan.

Extreme events such as floods, droughts, and heat waves can have major impacts on City Light hydroelectric project operations. Therefore, CIG analyses on the frequency and severity of extreme events in the Skagit River and Pend Oreille River watersheds were used to examine projected changes in extreme temperatures, extreme precipitation, and the occurrence of warm heavy precipitation. The Skagit Project operations model was used to assess the occurrence of spill events at Gorge Dam.

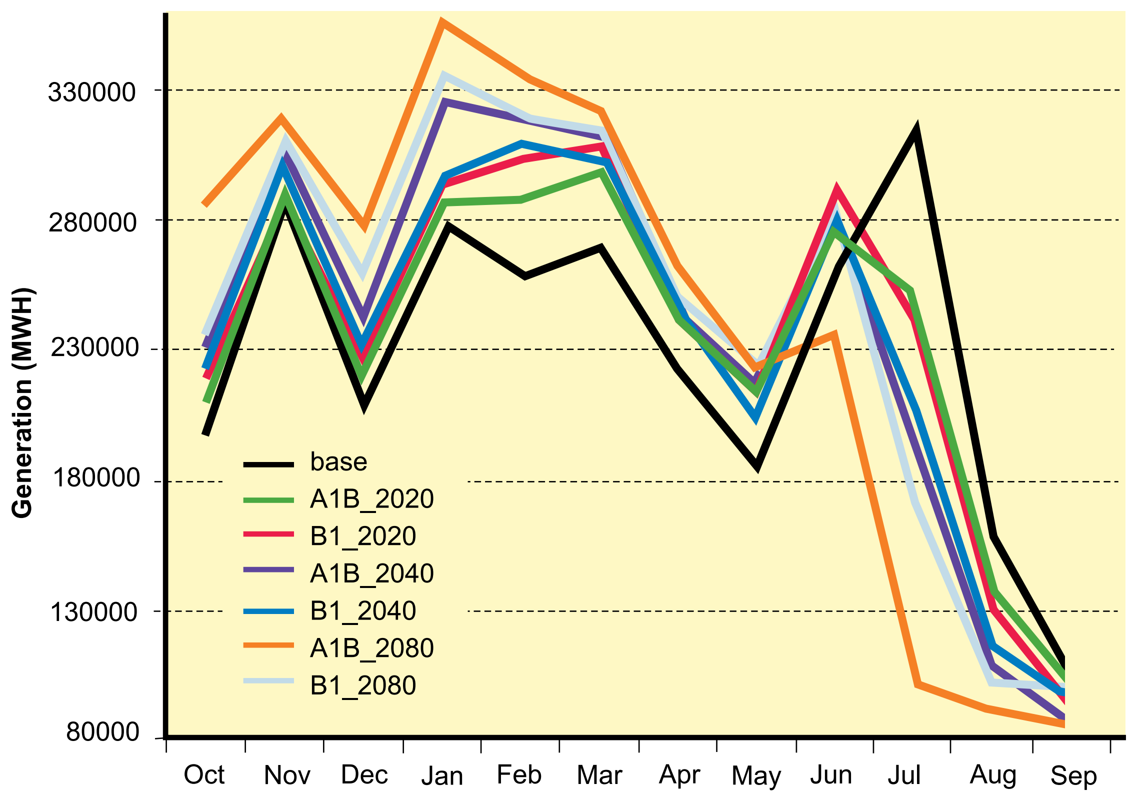
City Light has an obligation to protect salmonid habitat in and downstream of its hydroelectric projects. The Skagit Project is managed with very strict flow requirements to protect salmon, steelhead, and bull trout and their habitat. Therefore, City Light operations could be affected if there are changes to salmonid flow requirements mandated by the regulatory agencies. This appendix includes CIG (2010) analysis of climate change impacts to salmonids and their habitat from hydrologic and temperature changes so that City Light can make better informed decisions on possible project adaptation measures such as flow modifications and habitat protection actions.

Skagit River

Skagit Generation For this IRP analysis, City Light used the Skagit Project operations model that maximizes the value of power and simultaneously tries to meet the following requirements: (1) keep Ross Lake at normal fill from the end of June through the Labor Day weekend, (2) maintain the required flood control volume during November-March 15, and (3) not exceed maximum instream flows set for fisheries protection downstream of Gorge Powerhouse. The model currently does not include a summer low-flow criterion. It is important to remember that the model used here includes simplified operational constraints and produces generalized estimates of generation.

With future climate change, the estimated median annual generation for the Skagit Project is projected to increase by approximately 3% under the climate of the 2020s, 5% by the 2040s, and 9% by the 2080s. In general, generation would decrease in July, August, and September but increase in the other months and particularly in the late-winter and spring (Figure 3).

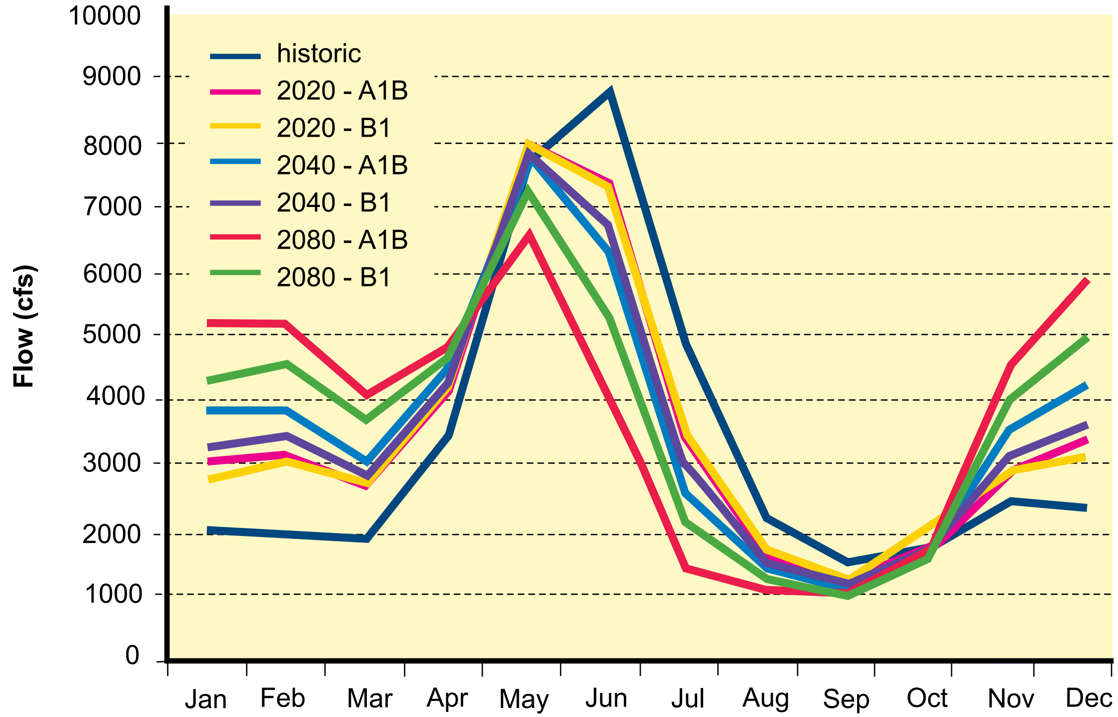
Figure 3. Effect of climate change on Skagit generation (model ensemble median values).



However, the degree to which the generation increases would be realized is highly dependent on being able to meet the multiple requirements for operating the project. For example, if outflows from dams need to change in response to modified flood control rule curves or downstream fish protection requirements, actual generation may be quite different from the model results. Also, if the actual precipitation differs much from the projections, the amount of generation could be dramatically different than what is presented here, particularly if there are more rain on snow events. Thus, it will be important to update these projections to reflect our most current understanding of climate change and fisheries needs, and new or modified regulations.

Skagit Hydrology and Operations The change in Skagit generation is due to the substantial changes in Ross inflows projected for the 21st century (Figure 4). Relative to the historical record, total annual inflow into Ross is actually projected to increase by 1-2% (based on average of ensemble of climate models). Flows will become substantially greater in the winter months but much lower during the summer and early fall (Figure 4). By the 2080s inflows during the winter months will be near May inflows, which is quite different from current patterns.

Figure 4. Mean monthly inflow into Ross Reservoir under historic baseline and climate change scenarios A1B and B1. Lines represent the model ensemble averages (CIG 2010).



This change in hydrology is due to a combination of changes in precipitation quantities, precipitation timing, and the reduced proportion of precipitation that falls as snow in the winter. The total precipitation is projected to increase during the fall and winter and decrease slightly in the summer (Figure 5, CIG 2009). The shift in precipitation timing along with the increased temperatures will cause substantial declines in the amount of water "stored" as snow (snow-water-equivalent [SWE]) (Figure 6).

An assessment of sensitivity of snowpack to increasing temperatures indicates that for every 1°C increase in temperature, the Skagit watershed would lose approximately 16% of its April snowpack and the date of melt out would advance 7 days (Casola 2009). Although changes to glaciers under future climates are not well understood, hydrology modeling indicates that the tributary inflow into Diablo Reservoir, which is greatly influenced by glacial runoff, will change dramatically under 2020 and 2040 climates. For example, glaciers in the Thunder Creek watershed contribute up to 57% of late summer creek flow, feeding directly into Diablo. (Chennault 2004). The June-September tributary flows from the glacier-fed streams are projected to decline dramatically later in the century as glaciers retreat or disappear (e.g., July could decline by 50% by the 2080s) (Figure 7).

Even under the 2020s climate, the summer-fall tributary flows would be 8-16% lower than baseline conditions. This projection is consistent with a study of glacial hydrology within the Thunder Creek watershed that estimates that climate change could reduce result late summer runoff by 18% by 2050 and more than 30% by 2100 (Chennault 2004). The reduced summer-fall flows will be accompanied by large increases in fall and winter runoff (Figure 7). The combination of altered Skagit River and tributary flows will create challenges in preventing spill events during the winter and maintaining adequate flows for fish downstream of Gorge dam during the summer.

Figure 5. Monthly precipitation at Ross Dam under historical baseline (blue) and A1B and B1 climate change emission scenarios (red) (CIG website).

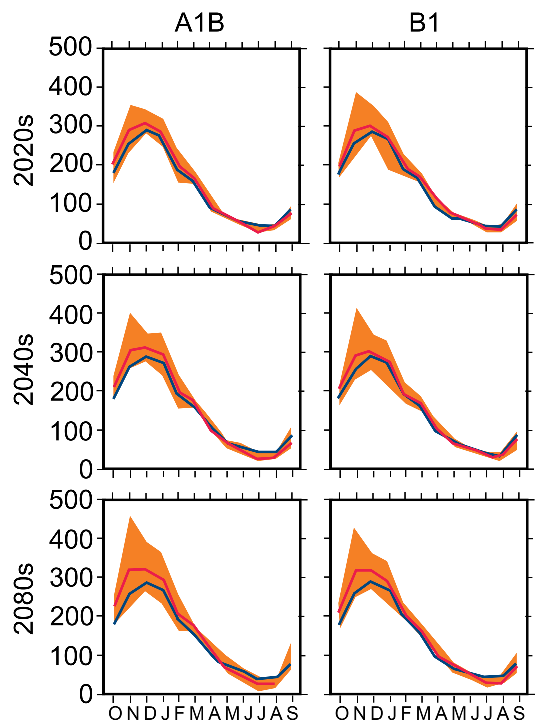


Figure 6. Effect of A1B and B1 climate change emission scenarios on snow-water-equivalent (SWE) at Ross Dam. Blue line is baseline and red line is ensemble average (CIG website).

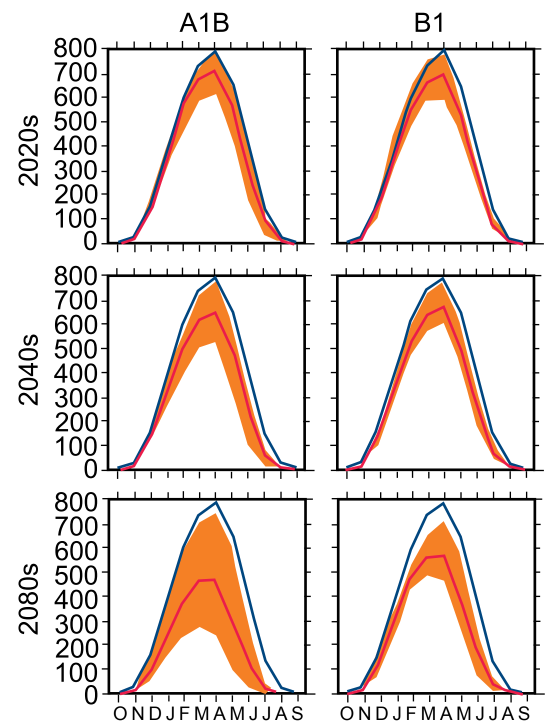


Figure 7. Effect of climate change on Diablo Reservoir tributary inflow (median) under scenario A1B (medium-level emissions) and B1 (low-level emission).

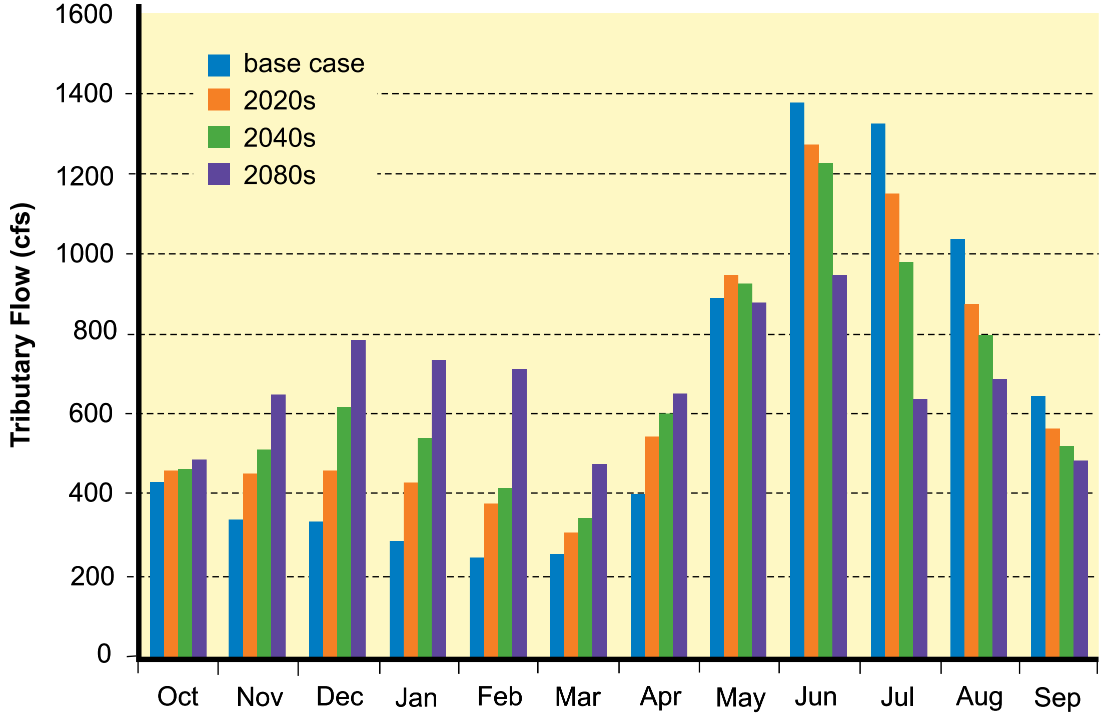
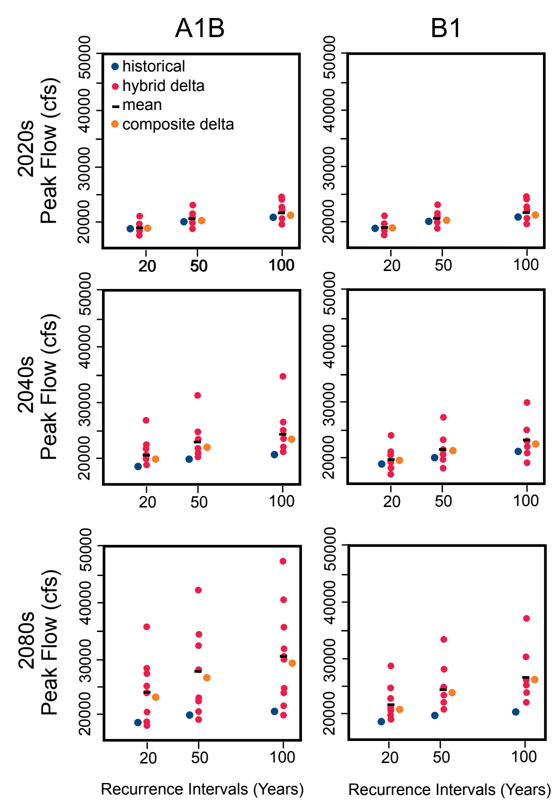


Figure 8. Effect of A1B and B1 climate change emission scenarios on 20-, 50-, and 100-year return interval flood magnitude at Ross Dam (CIG 2010).



Precipitation intensity may increase above current conditions at Diablo Dam (CIG 2010), although climate models are still unable to accurately predict the frequency and magnitude of major storms such as "Pineapple Express" events that cause spill events and lost generation at Skagit. The magnitudes of the 20-, 50-, and 100-year-return flood events at Ross are expected to increase 1, 10, and 15%, respectively in the 2020s under the B1 scenario (Figure 8). By the 2040s, the flood flows would be 5, 15, and 22% greater than current levels (CIG 2010). Much of the projected increase in peak flows would occur during the late fall and early winter because an increased percent of precipitation will fall as rain instead of snow, resulting in an increased contributing runoff area.

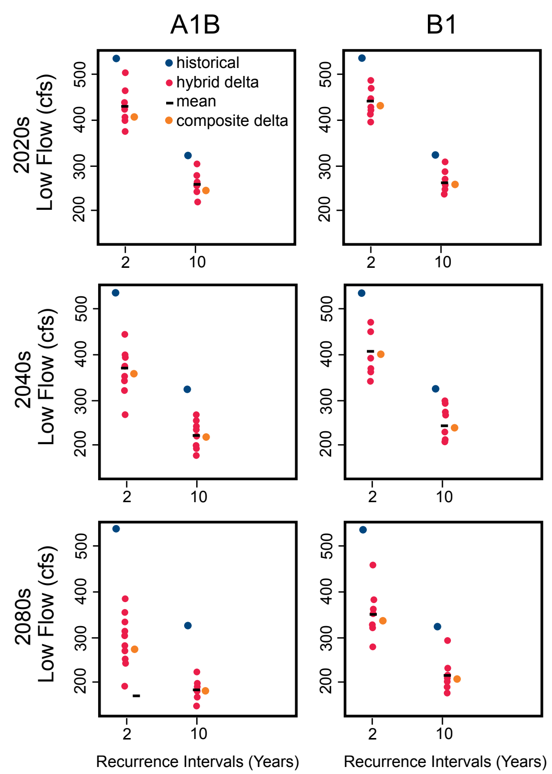
Climate change will also cause lower inflows into Ross Lake during the summer that could affect project operations. The 1-, 3-, and 7-day Ross low inflows are projected to decrease approximately 100 cfs (17-20%) under the 2020s climate and an additional 10% by the 2040s (Table 1). The 10-year return low flow for Ross Reservoir would decline significantly by the 2020s (Figure 9).

Table 1. Change in low flow statistics (cfs) for Ross Reservoir inflows with climate change.[1]

Flow statistic	Historical	2020s	2040s
1-day minimum	479	385	346
3-day minimum	501	408	369
7-day minimum	568	472	429

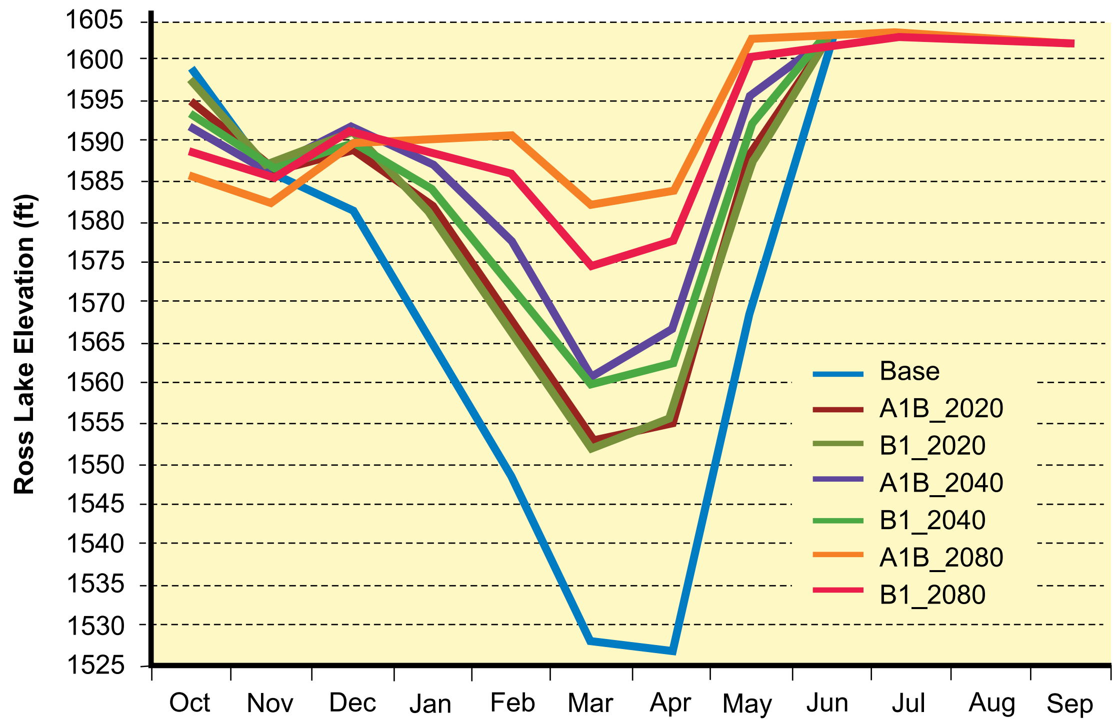
[1] Combined model ensemble average of A1B and B1 scenarios.

Figure 9. Effect of climate change on the 7-day minimum low flow statistics with a 2-year and 10-year return interval for the Ross reservoir for the A1B and B1 scenarios (CIG 2010).



With future climate change, the Ross Lake pool would likely be held at higher levels during the winter and spring because there will not be as much snowpack associated runoff. Winter Ross Lake drawdown could be 30 ft less than under baseline conditions with the climate of the 2020s, and 35 ft less with the 2040s climate (Figure 10). While nearly 90% of the drawdowns are below 1,560 ft under the base case, less than 50% of years would have lake levels below that level under the 2040s climate. The higher spring pool levels would increase the probability that full pool of 1,602.5 ft is achieved by the end of June for the recreation season (Table 2). However, operating Ross Lake at higher pool levels would also increase the chance of spill when high flow events do occur.

Figure 10. Median Ross Lake End of Month Level under simulated historical (base case) and future climate change conditions under the A1B and B1 emission scenarios (ensemble averages).



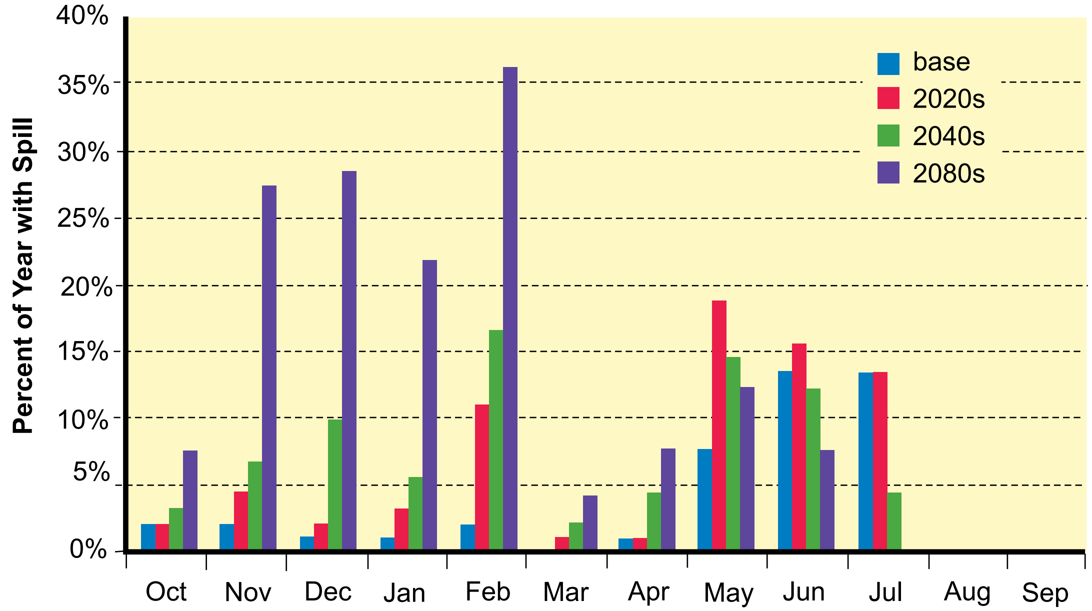
The Ross Lake level must be at or below the flood control pool elevation of 1,592 ft between December 1 and March 15. Under the baseline conditions, the November through March end-of-month pool levels are consistently under the required level every year and 95% of the years have March levels below 1,570 ft. As the climate warms, the probability of the lake level going above 1,592 ft between the end of the current flood control season (March 15) and the end of March increases 3% in 2020s, 11% in the 2040s, and 26% in the 2080s (Table 2). Thus, there would be an increased chance of spill without further operational modifications. This analysis does not account for the possibility that the Corps of Engineers may alter flood control rule curves in the future.

Table 2. Effect of climate change (emission scenario A1B) on Ross Lake levels during recreation and end of flood control season.

Month End Statistics	Historical	2020s	2040s	2080s
Recreation Season Requirement (>1,602 ft July 1 - Labor Day)				
June Avg. Pool Level	1595.6	1601.3	1602.8	1603.4
June 5th Percentile	1570.3	1592.6	1601.9	1602.4
% June Pool < 1602 ft	47%	18%	5%	0%
August Avg. Pool Level	1601.5	1602.0	1602.3	1602.7
August 5th Percentile	1598.0	1599.0	1598.3	1600.1
% August < 1602 ft	36%	34%	30%	22%
Flood Control Requirement (<1,592 ft November 1 - March 15th)				
March Avg. Pool Level	1525.2	1548.3	1559.4	1578.4
March 95th Percentile	1571.0	1582.8	1590.7	1596.0
% March > 1592 ft	0%	0%	4%	20%
Based on 91-year record historical data and emission scenario A1B				

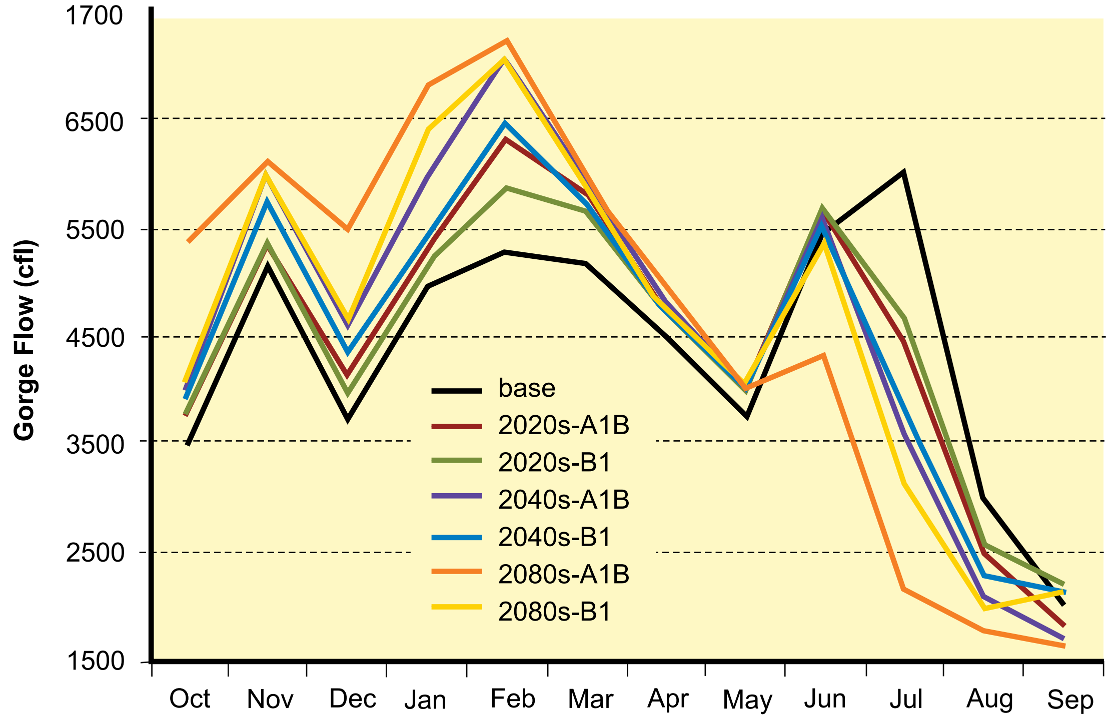
City Light attempts to minimize the amount of spill since it cannot be used for electricity generation. It is difficult to produce accurate estimates of spill by analysis of average monthly flows, but estimates show changes in spill seasonality and magnitude. Since there will be less of a summer peak for inflows, there will also be less frequent June-July spill, but the chance of spill increases in most other months (Figure 11). For the months of November and December, the projected number of years with spill increases from 1-2% currently to 7-10% in the 2040s and 27-29% by the 2080s. Winter spills will also tend to become substantially larger with climate change. While there is no way to determine the effect of climate change on future fine-scale storm paths, the analysis completed by CIG (2010) found that there is a statistically significant increase in the number of warm days with heavy precipitation by the 2040s at many of the stations assessed in the Skagit River watershed. The increase in warm-wet events that often trigger spills appears to be driven primarily by increases in temperature rather than precipitation. If more frequent and larger spills occur, projected increases in fall-winter generation could be reduced.

Figure 11. Effect of climate change on monthly incidence of spill at Gorge Dam under A1B emission scenario.



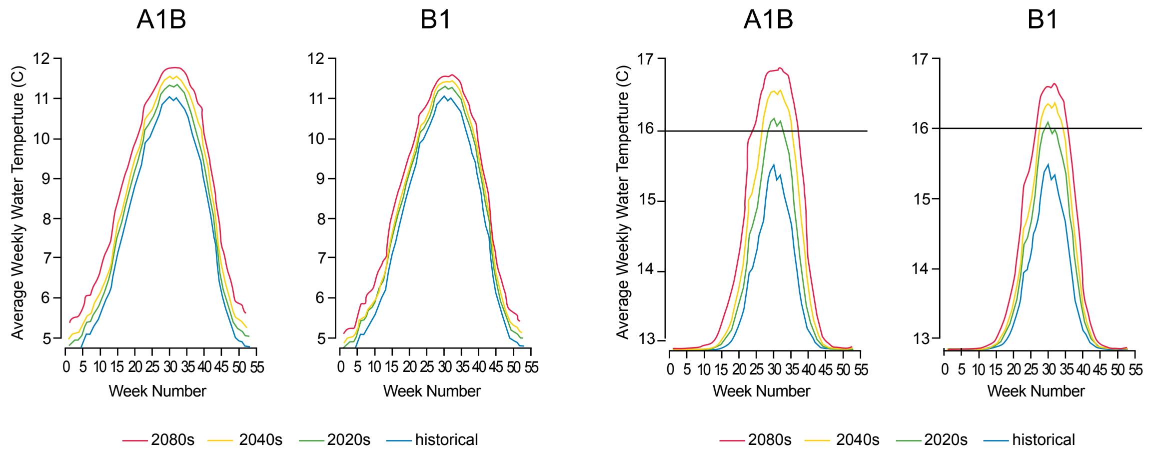
Skagit Fisheries Because City Light protects fish populations and salmonid spawning, rearing, and foraging habitat in the Skagit River between Newhalem and Marblemount, it closely monitors flow conditions at both stream gage locations. When tributary flows entering the Skagit River between Newhalem and Marblemount are very low during the summer, City Light releases additional water from the project to maintain adequate flows for fish. Projections indicate that the natural hydrograph in the later portion of the 21st century will have 50% lower June-August flows but much higher fall and winter flows (Figure 12). Higher fall flows would result in salmon spawning at higher elevations in the channel, increasing requirements for higher flows throughout the winter to protect salmon redds. By the 2040s, the altered hydrology will increase the risk that flows downstream of Gorge will exceed current maximum thresholds established for fisheries protection in each month except July-September. Projections suggest little change in the frequency of flows exceeding 18,000 cfs, which is the approximate Chinook salmon redd scouring flow. However, the frequency of flows over 25,000 cfs, which is the approximate bank full event and gravel movement threshold, would approximately double by 2080 compared to baseline conditions.

Figure 12. Effect of climate change on Gorge flows.



Projected 21st century temperature increases will reduce the length of time that some river reaches and tributaries have temperatures suitable for cold-water fish species (CIG 2010). While CIG (2010) analysis shows current and project weekly temperatures at Marblemount remaining below the threshold (Figure 13), it does indicate a substantial increase in August and September water temperatures, so it is quite likely that the incidence of temperatures above 13°C will increase in the mainstem Skagit River.

Figure 13. Projected weekly average water temperatures averaged over each time period for the A1B and the B1 scenarios for the Skagit River at Marblemount (left) and Sedro Woolley (right).



Several major tributaries to the Skagit Hydroelectric Project are projected to have longer periods when water temperatures are not only above 13°C, but also above suitable "core" salmonid habitat (16°C) (Figure 14). Because this analysis does not incorporate changes in flows and relative contribution by melting snowpack and glaciers, summer water temperatures could increase more than what is indicated in this analysis if glacial runoff declines or disappears.

The substantial reduction in July-September flows (Figure 12) and increased water temperatures will further reduce the amount of available habitat for juvenile salmonids that remain in freshwater for long periods of time (steelhead, Chinook and coho). Fish that spawn in the Skagit River in October-December (Chinook, chum, and coho) will be spawning at flows that are 20-30% greater. This could be problematic for fish populations if there aren't associated increases in tributary flows in the late-winter through spring for redd protection during incubation and emergence. Although flows would increase in January-April, it appears that the increases in March and April are small relative to the increases in spawning flows. Lower flows in March-April could lead to egg-to-emergence survival rates that are lower than current levels. City Light will need to continue to assess potential effects on salmon and may need to adjust project releases to protect them.

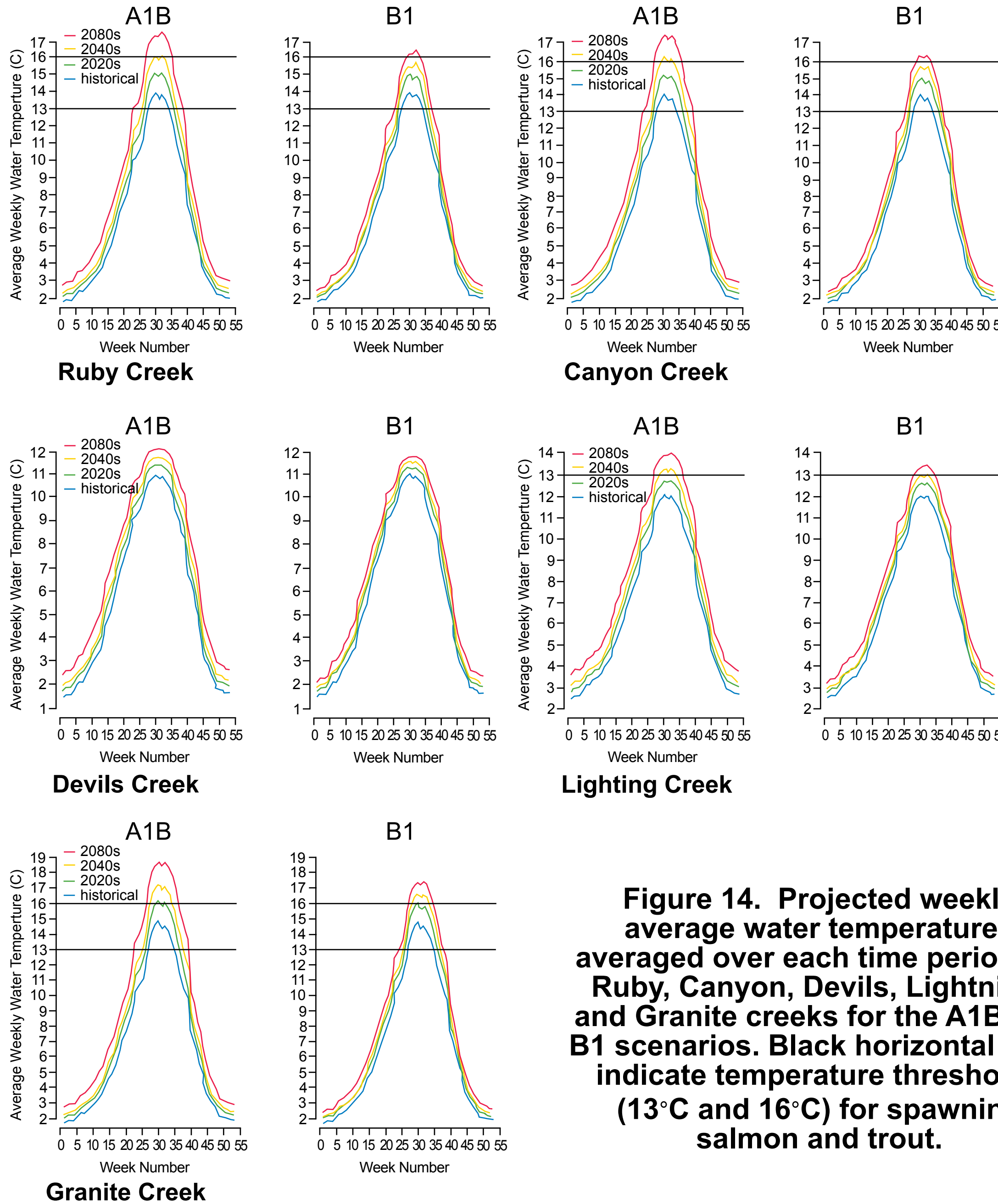
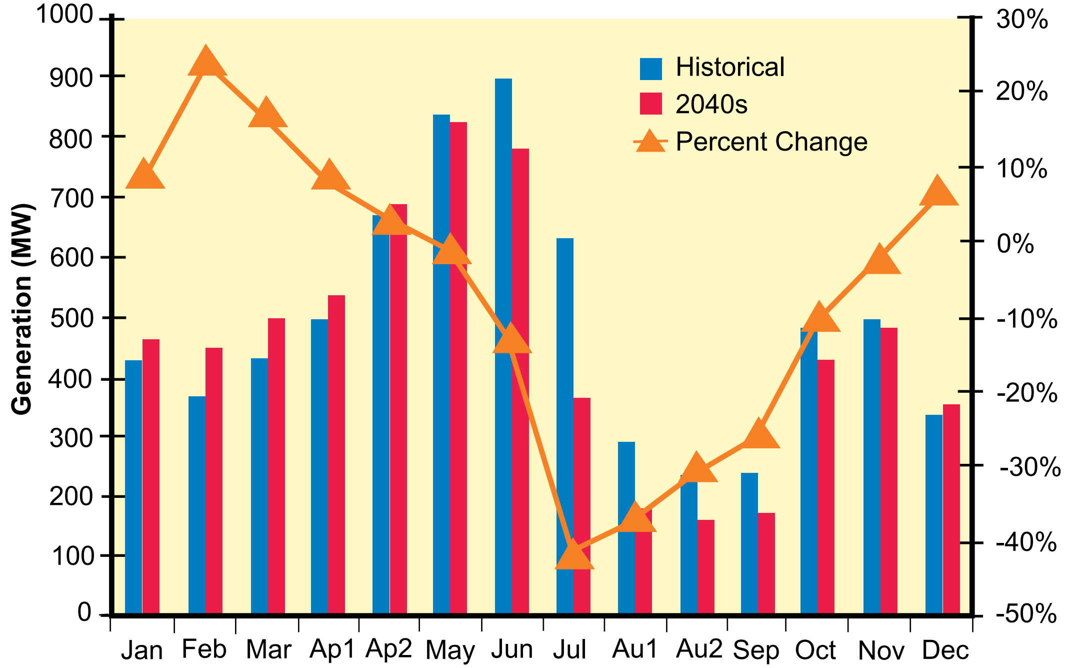


Figure 14. Projected weekly average water temperatures averaged over each time period for Ruby, Canyon, Devils, Lightning, and Granite creeks for the A1B and B1 scenarios. Black horizontal lines indicate temperature thresholds (13°C and 16°C) for spawning salmon and trout.

Boundary

Boundary Generation To assess impacts to Boundary generation, City Light used the NPCC Sixth Power Plan data, including projected generation for the 2040s vs. historic conditions for emission scenario A1B. Total annual Boundary generation is projected to decline by approximately 7 % based on the NPCC data. There will be substantial declines in June-September, with July and August being most severe in the projections (Figure 15).
This decline will be partially offset by moderate increases in January - April (Figure 15) (NPCC unpublished data). The actual changes in Boundary generation are very difficult to estimate. Not only are the projections based on climate models with a level of uncertainty, but inflow is controlled by upstream dams that may change operations in the future.

Figure 15. Comparison of Boundary Project generation under historical and 2040 simulated climate conditions (emission scenario A1B model ensemble average) (Source: NPCC unpublished data).



Boundary Hydrology and Operations At the Boundary Project, climate change is projected to result in reduced June-September inflows, relatively little change in October, and increased inflows during November-May (Figure 16). This assumes no major changes in the operation of the upstream hydroelectric projects. This pattern generally follows the projected future pattern of precipitation (Figure 17). While there is variation among model projections, the 10-, 20-, and 50-year flood flows are not projected to change much through the 2040s at Boundary Dam (Figure 18). Summer 7-day low-flows are projected to decline at Boundary by 5% by the 2040s (Figure 19).

Figure 16. Effect of climate change on mean monthly inflow into Boundary Reservoir under climate change scenarios A1B and B1. Lines represent the model ensemble averages (CIG 2010).

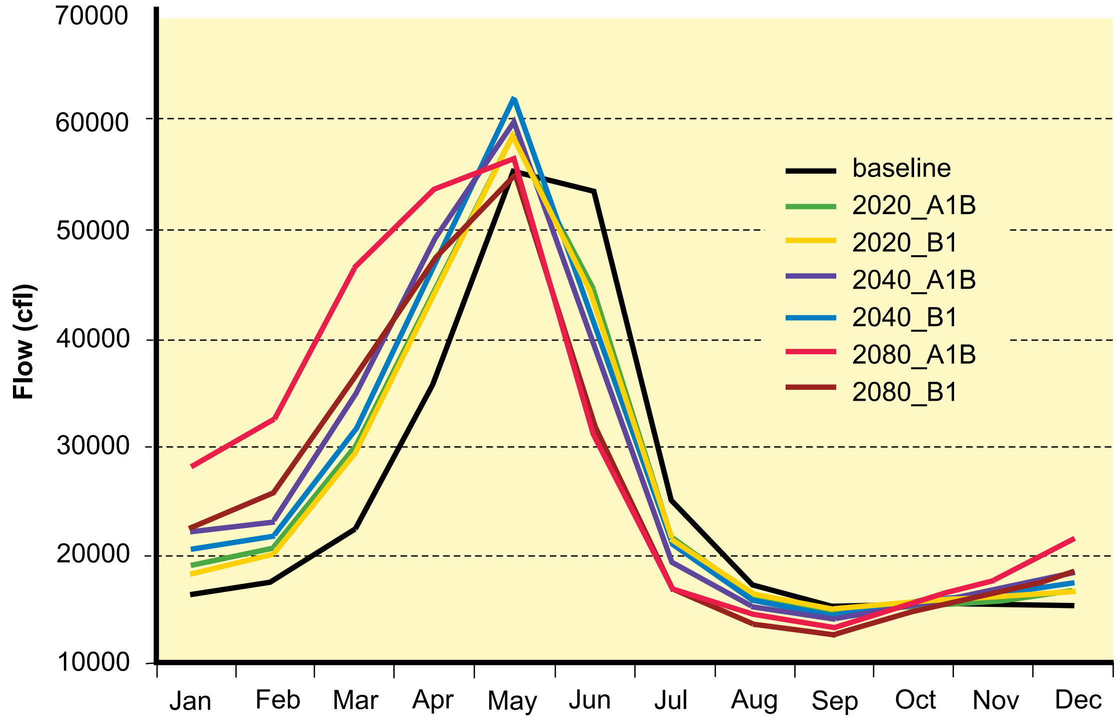


Figure 17. Effect of A1B and B1 climate change emission scenarios on monthly precipitation at Boundary Dam. Blue line is baseline and red line is model ensemble average (CIG website).

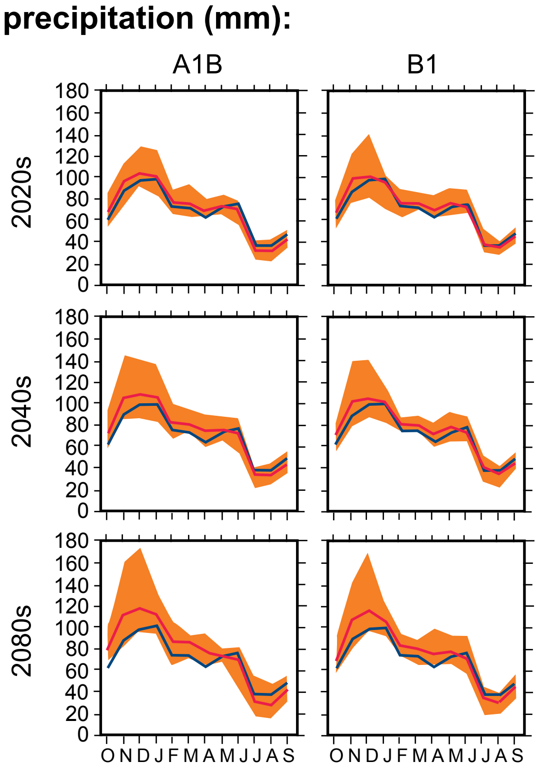


Figure 18. Effect of A1B and B1 climate change emission scenarios on 20-, 50-, and 100-year return interval flood magnitude at Boundary Dam.

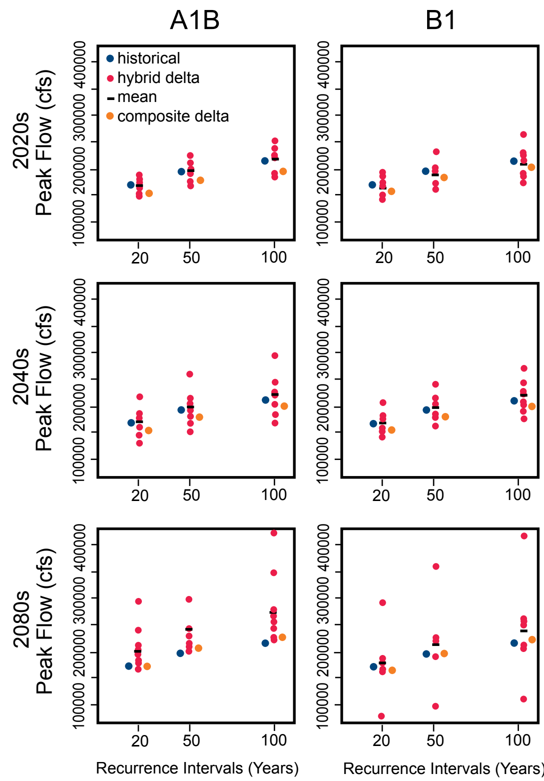
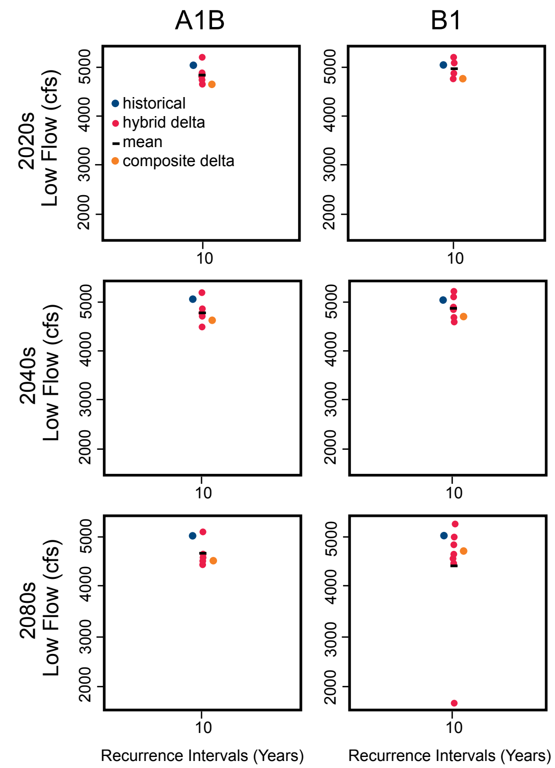
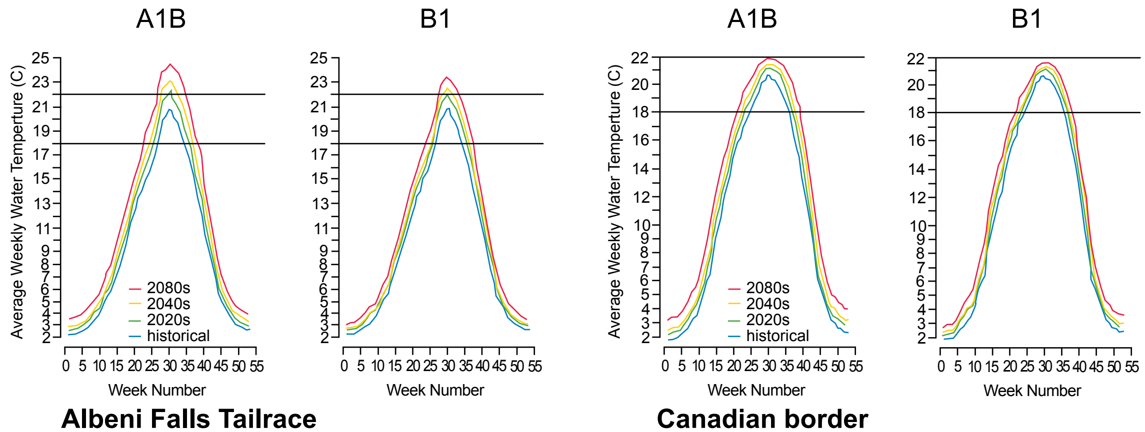


Figure 19. Effect of climate change on the 7-day minimum low flow statistics with a 10-year return interval for the Boundary Dam for the A1B and B1 scenarios (CIG website).



Boundary Fisheries Climate change is projected to result in increasing water temperatures that will lengthen the time that the Pend Oreille River exceeds the threshold for bull trout avoidance (18°C) and will result in increased risk of temperatures exceeding the 22°C threshold for trout avoidance and reduced growth and lethal level for bull trout (Figure 20). The increases are projected to be most severe upstream of the Boundary Project. The increased water temperatures will need to be considered in planning fisheries protection and enhancement options.

Figure 20. Projected weekly average water temperatures averaged over each time period for Pend Oreille River at Albeni Falls tailrace and Washington-Canada border. Horizontal lines represent the 18°C and 22°C temperature thresholds for spawning salmon and trout.



Data Gaps

The following data gaps will be the focus for improving our understanding of climate change impacts to City Light operations.

Glaciers

An important consideration that cannot yet be well-incorporated in this analysis is the consequence of melting glaciers in the Skagit River watershed. Many glaciers in the North Cascades have already disappeared and most of the remaining glaciers are receding and thinning. As they shrink in size, their contribution to summer flows will decrease. There is not a large glacial contribution to inflows at Ross, but glaciers are important sources of flow for Thunder Creek, a tributary to Diablo Lake, and the Cascade, a tributary at Marblemount. Not only will flows be reduced but without the contribution of melting ice, the water will be warmer, with potential important consequences for fish. Additional glaciological information is being collected by the National Park Service and other researchers and will be incorporated into future assessments.

Improved modeling of glaciers and tributary hydrology is needed to refine our assessment of climate change impacts on hydrology of the Skagit River over the next century.

Storm Forecasts

While there has been some improvement in regional climate modeling, there still is no way to estimate how climate change may affect the incidence of storm events. Often times, subtle changes in storm tracks lead to “atmospheric rivers” where warm rain-on-snow “Pineapple Express” events affect the Skagit River watershed during the late-fall and winter periods. These events result in very high peak flows and often cause City Light to spill water at the project.

Skagit Fisheries Downstream of Newhalem

City Light will continue to research the relationships between hydrology and fisheries populations and survival and will incorporate that information into long-term operational planning. Data from ongoing monitoring of salmonid populations will be used to evaluate flow management options for meeting life cycle requirements. In particular, it will be very important to gain more information on the hydrology of tributaries between Newhalem and Marblemount.

Climate and Operational Model Improvements

City Light will monitor the continuing evolution of climate science models that may improve resolution and reduce uncertainty of future climate change projections. New models will attempt to incorporate decadal prediction simulations that may help evaluate the interaction between long-term climate changes and the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) climatic cycles that play such a major role in snowpack in the North Cascades.

City Light will also work to improve the Skagit operations model used to evaluate projected hydrology data. The current model incorporates reservoir and flow constraints, but additional refinement that would enable scenario simulations to test assumptions and operation options, improving our understanding and risk assessment.

Infrastructure Planning

City Light needs to incorporate climate change-induced impacts on Sea Level Rise (SLR) and hydroelectric operations into capital project planning and assessment management to inform decisions on proper siting and design of facilities (e.g., transmission and distribution assets located near shorelines, reservoir intakes, powerhouse tailraces, boat launches, etc.).

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